



U.S. DEPARTMENT OF
ENERGY

Nuclear Energy

Fuel Cycle Research and Development Overview

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U.S. Direction on Future Fuel Cycles

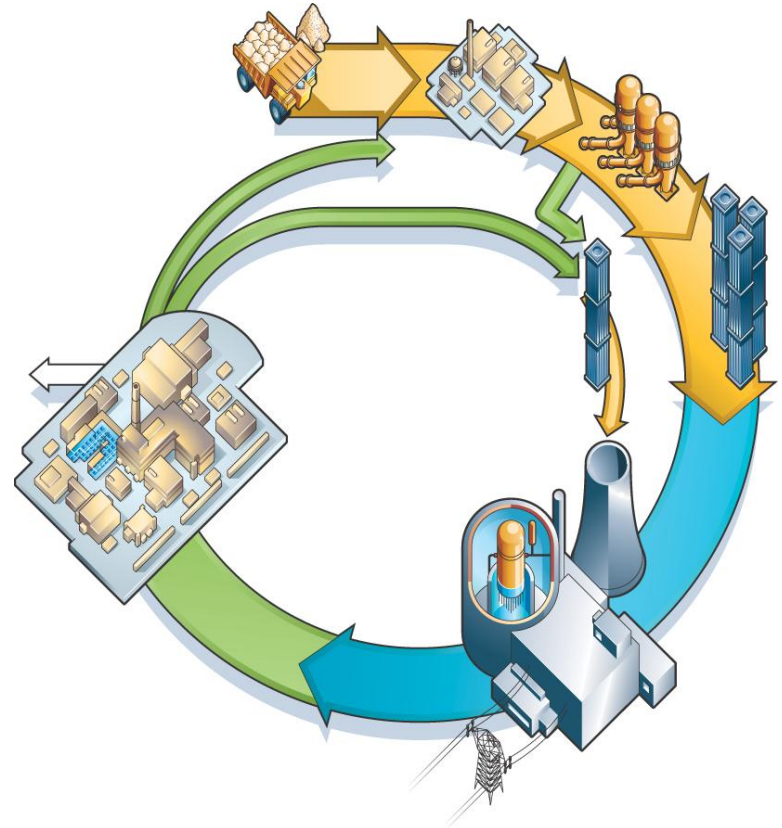
- **U.S. has decided that used nuclear fuel storage in dry casks is safe for many decades.**
 - U.S. has no immediate need to implement used fuel reprocessing or geologic disposal.
- **DOE has established a goal-oriented, science-based research and development program to provide fuel cycle and used fuel management options to future decision makers.**
- **If the U.S. chooses to recycle, deployed technologies must be cost effective, safe, environmentally sound and have low proliferation and security risk.**
- **Blue Ribbon Commission will provide a policy/planning framework that will guide FCRD.**



Recycle of Used Fuel

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- Option to recycle used fuel has been the subject of much debate and discussion.
- Nonproliferation issues and economics have limited recycle options.
- Recycle of used fuel enables increased utilization of resources and potential waste management benefits.
 - Once through fuel cycle uses less than 1% of energy value of the uranium.

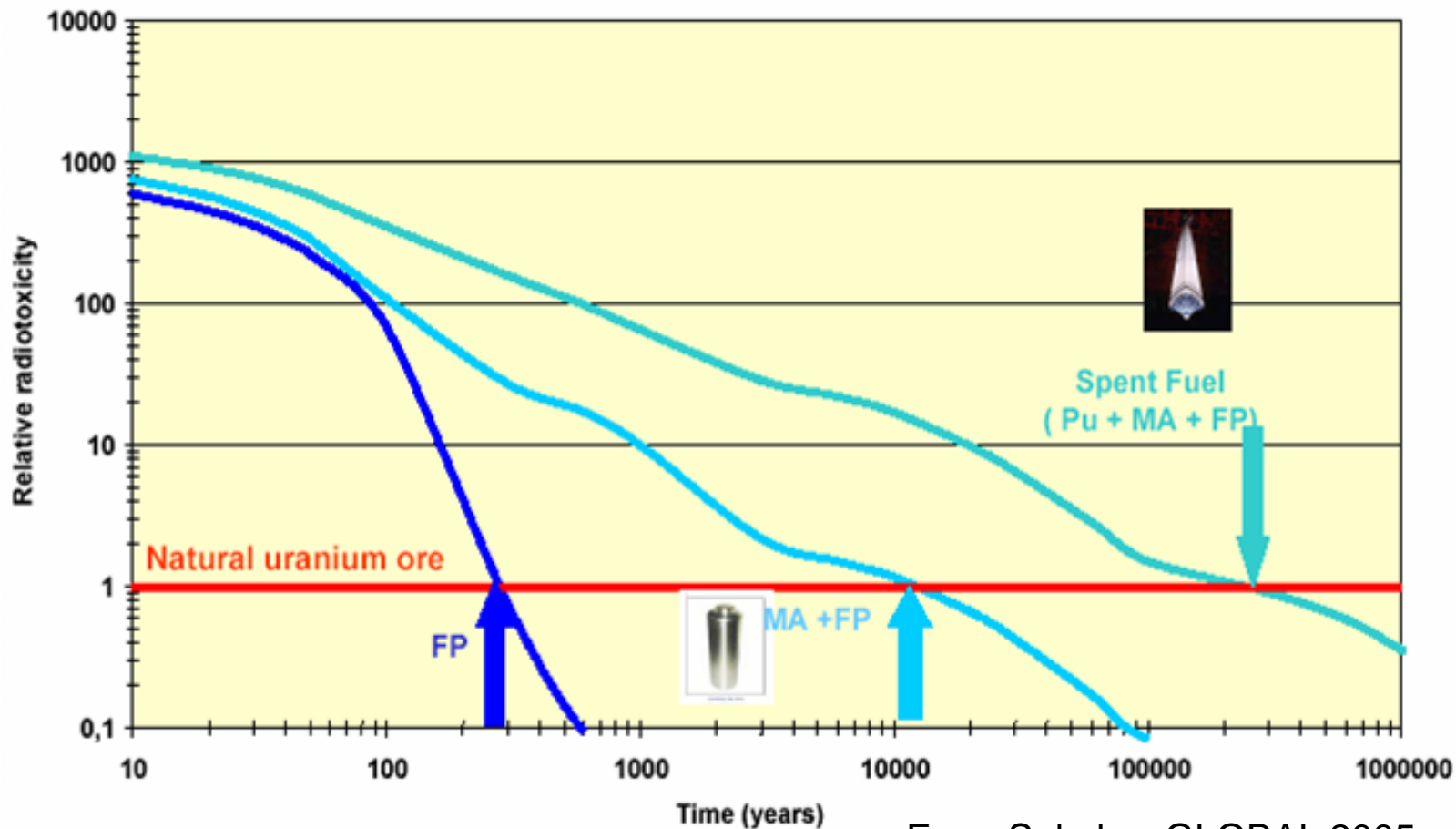


Courtesy AREVA



Recycling May Reduce Future Risk

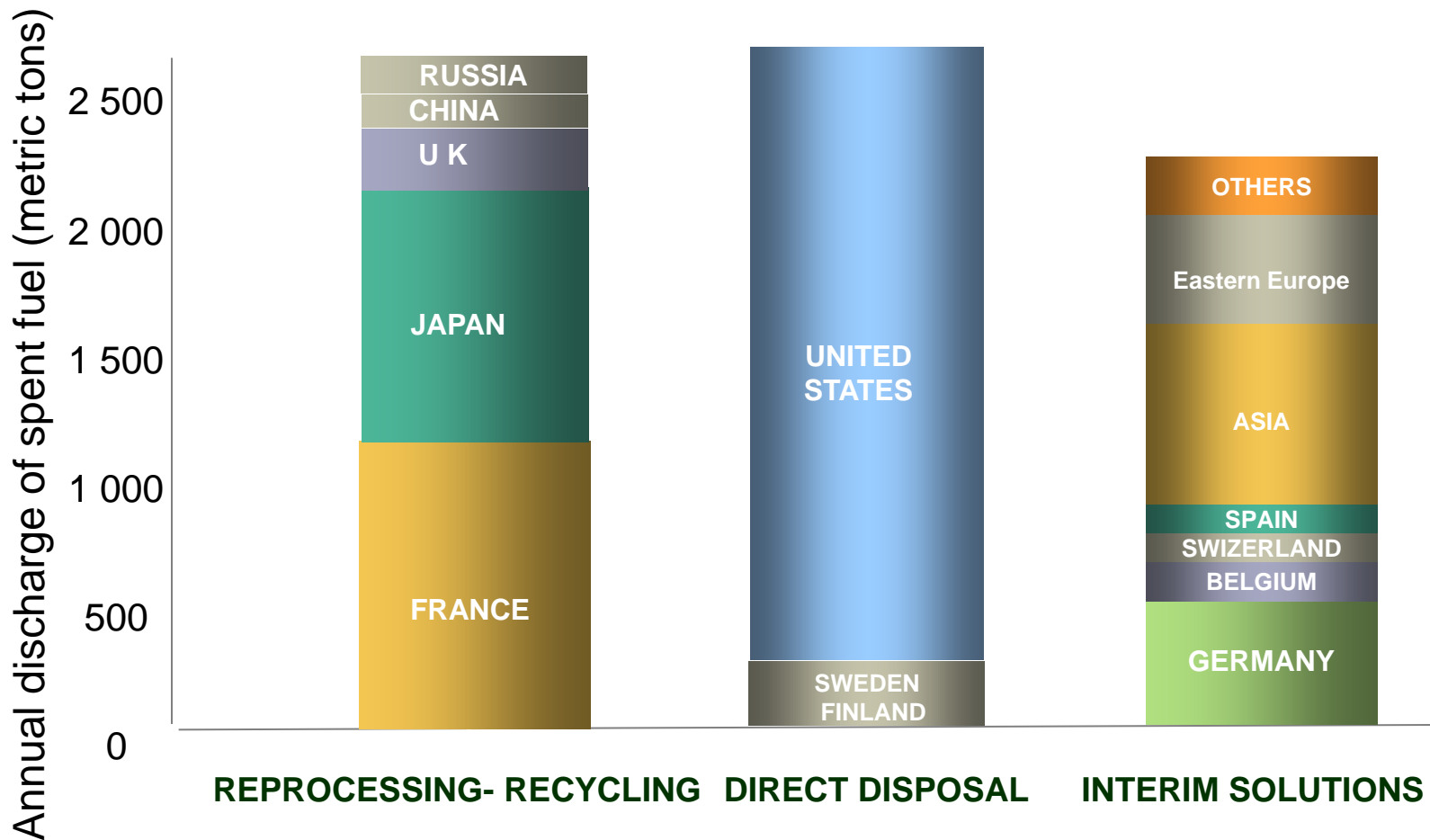
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From Sokolov, GLOBAL 2005

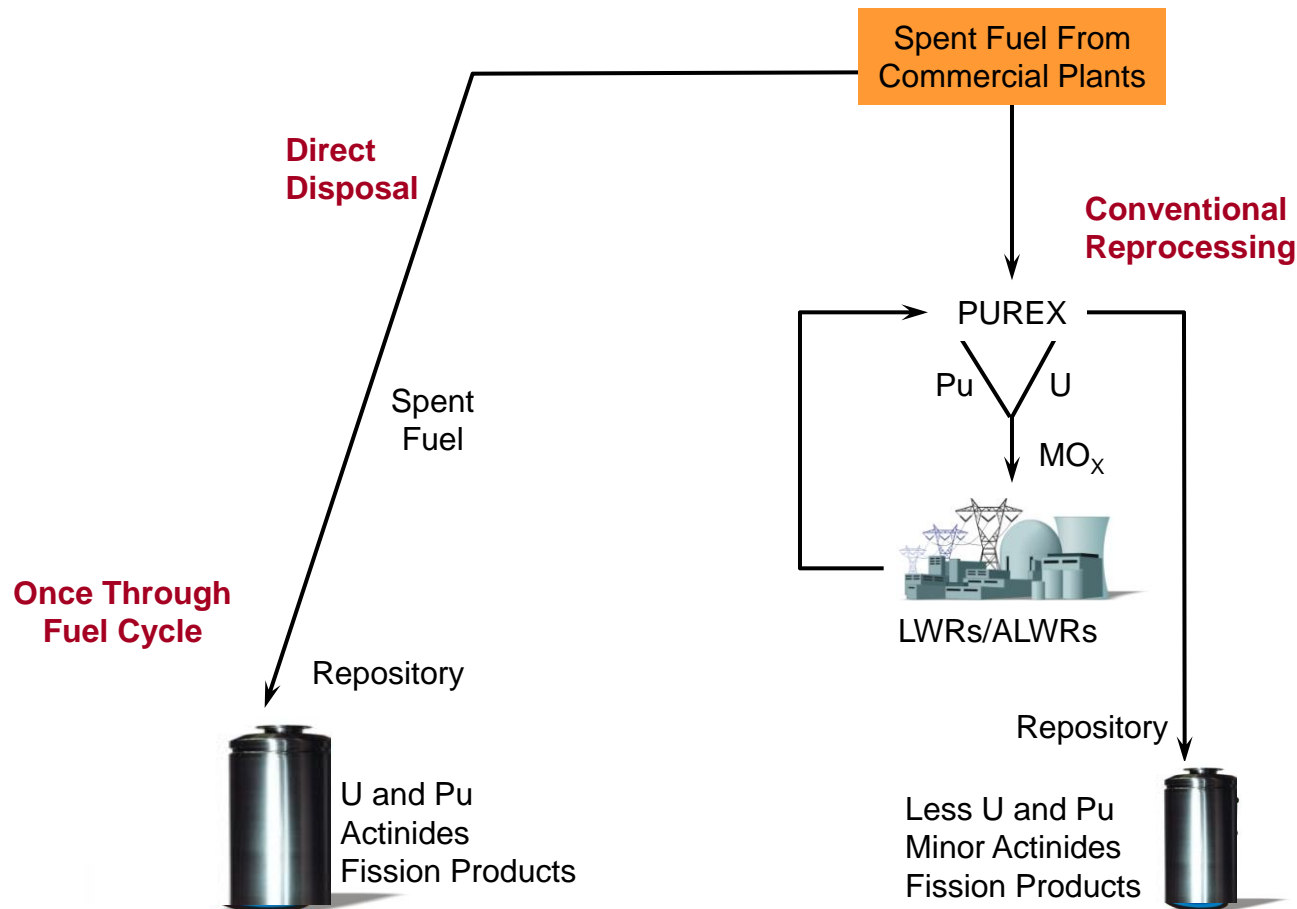


National Policies Concerning Used Fuel





Current World Fuel Cycles



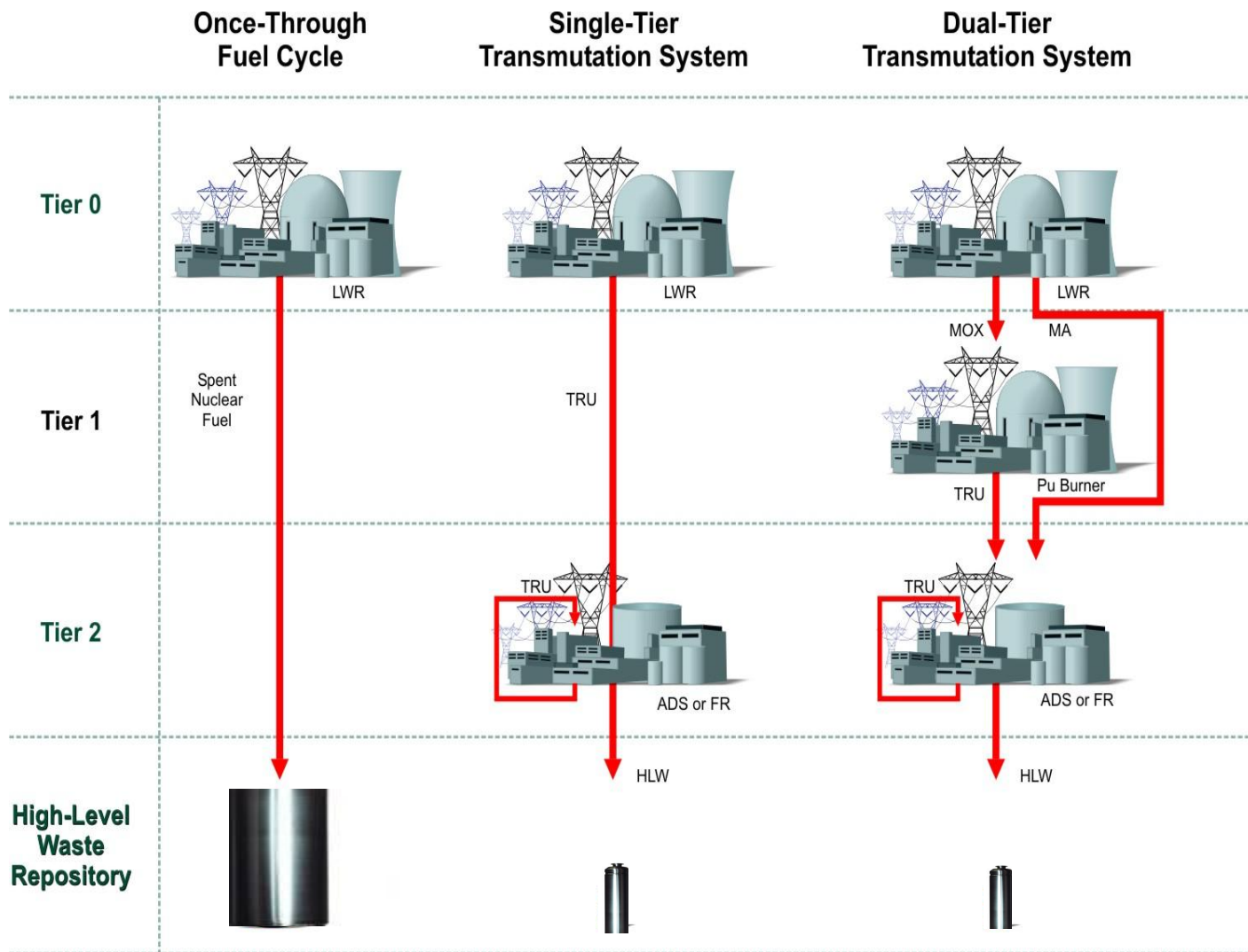
- Although referred to as closed, the currently deployed fuel cycle with reprocessing results in significant transuranics disposed and low uranium utilization.

European/Japanese
Fuel Cycles



Past Programs Addressed Primarily Once-Through and Full Recycle

- Minimum research focused on improving once through.
- Both single (not recycle to LWRs) and dual tier approaches explored for full recycle.





Changes: Advanced Fuel Cycle Initiative (w/GNEP) to Fuel Cycle Research and Development

Advanced Fuel Cycle Initiative With GNEP

- Incremental improvement of existing technologies
- Driven by better utilization of Yucca Mountain repository
- Focused on near-term technology deployment

Fuel Cycle Research and Development

- Transformational breakthroughs
- Unconstrained range of storage and disposal options
- Long-term, goal-oriented, science-based approach



Objective 3 - Enable Sustainable Fuel Cycle: Objectives

- **Near Term - Define and analyze fuel cycle technologies to develop options that increase sustainability of nuclear energy**
- **Medium Term – Select preferred fuel cycle option for further development**
- **Long-term (2050) – Deploy preferred fuel cycle**





- **Separations and Waste Forms**
- **Advanced Fuels**
- **Transmutation**
- **Modeling and Simulation**
- **Materials Protection, Accounting, and Control for Transmutation**
- **Used Nuclear Fuel Disposition**

- **FCRD also has a extensive System's Analysis activity used to evaluate and assess various fuel cycle options and issues.**



Separations and Waste Forms

Today's Technology Challenges

- Meeting current air emission requirements
- Economical recovery of transuranic elements for recycle/transmutation
- Minimal waste generation

Grand Challenges

- Near-zero radioactive off-gas emissions
- Simplified, single-step recovery of transuranic elements
- Significantly less process wastes



Development Path

- Develop fundamental understanding of separation process and waste form thermodynamics
- Understand underlying separation driving forces
- Exploit thermodynamic properties to effect separations
- Elucidate microstructural waste form corrosion mechanisms

Transformational Result

- Predictive capability for separation and waste form performance over a broad range of operational conditions
- Novel separations technologies



Today's Technology Challenges

- Fuels with variable compositions
- Understanding and predicting fuel behavior and performance
- Reliably fabricating fuel with zero defects and with minimal process losses

Grand Challenge

Fast reactor fuels with multi-fold increases in performance over previous generation fuels, with very low fabrication losses, and that permit high transmutation of radiotoxic elements



Development Path

- Develop a μ -structural understanding of fuels and materials
- Closure of combined transport and phase-field equations
- Separate effect testing and properties measurement at sub-grain scale
- Effect of nano-scale implantations
- Innovative clean and reliable fabrication techniques with tightly controlled microstructures tailored to desired performance

Transformational Result

- Predictive capability for fuel process and in-pile behavior for a variety of initial and boundary conditions
- Novel fuel forms

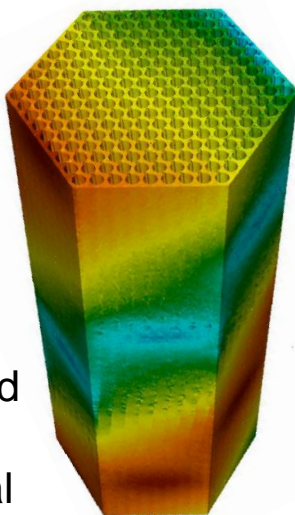


Today's Technology Challenges

- Current generation of nuclear modeling and simulation tools are empirically based
- Limited to use only for conditions very close to those experiments

Grand Challenge

Rapidly create and deploy "science" (1st principles) verified and validated modeling and simulation capabilities essential for the design, implementation, and operation of future nuclear energy systems with the goal of improving U.S. energy security.



Development Path

- Create teams focused on developing Integrated Performance and Safety Codes
- Support smaller projects developing atomistic scale models and methods for upscaling to integrated codes
- Develop and implement methodologies for verification, validation and uncertainty quantification
- Ensure capability transfer pathways to users of modeling and simulation capabilities (labs, industry and regulatory agencies)
- Provide supporting computational technologies

Transformational Result

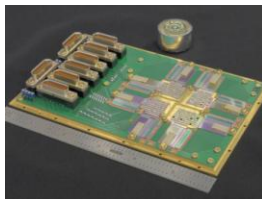
Develop modeling and simulation that is on par with theory and experiment to implement a modern science based approach for fuel cycle technologies.



Materials Protection, Accounting, and Control for Transmutation

Today's Technology Challenges

- Large throughput facilities require shutdown for periodic inventory
- New reactor designs require new nuclear material management approach
- Move from reactive to preventive systems approach



Grand Challenge

Develop online, real-time, continuous, accountability instruments and techniques that permit an order of magnitude improvement in the ability to inventory fissile materials in domestic fuel cycle systems, in order to detect diversion and prevent misuse

Development Path

- **Next generation instrumentation**
 - High sensitivity and specificity
 - Enabled by new physics data
 - New sensor materials
- **Integration of disparate data in quantitative manner**
 - Real time assessments
 - Probability basis with uncertainties
- **Predictive modeling and simulation at atomistic and plant level**

Transformational Result

Real time nuclear materials management
with continuous inventory



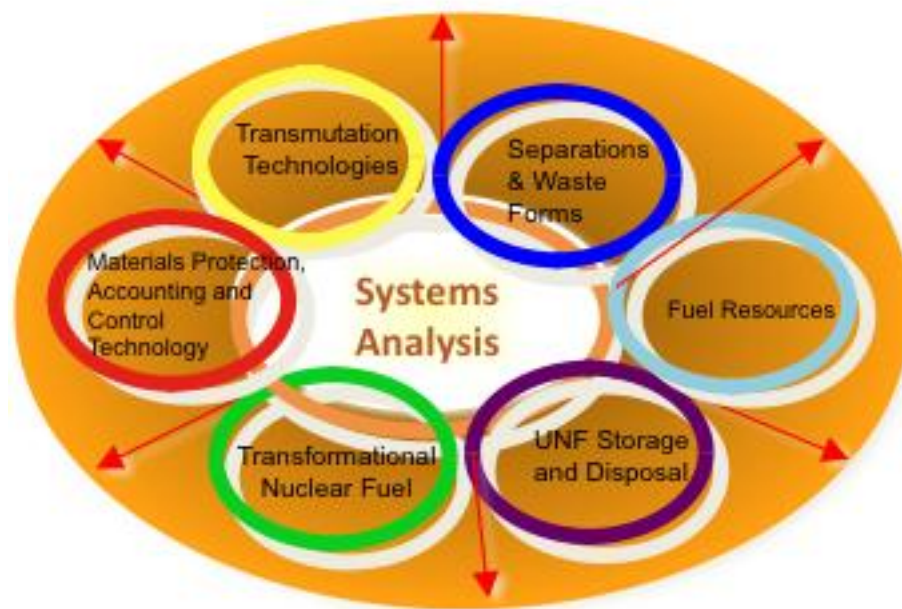
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Systems Analysis in the Fuel Cycle R&D Program

- **Mission: Perform integrating analyses of nuclear energy and fuel cycle systems to inform fuel cycle R&D, programmatic decisions, strategy formulation, and policy development**
- **Enables examination of a diverse set of scenarios**
 - Evaluate technology alternatives
 - Evaluate gaps, disconnects, and off-ramps
 - Examine deployment options
 - Understand system dynamics
 - Identify critical program elements to inform where R&D should be targeted
- **A multiphase fuel cycle options study is ongoing.**



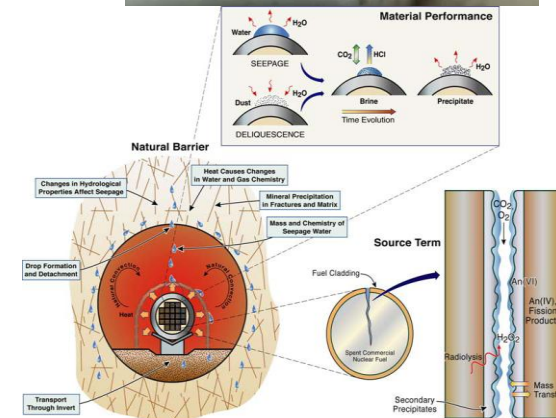
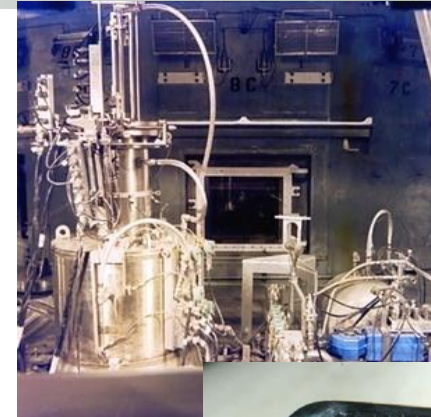
Systems analysis is a predictive/strategic tool, enabling a proactive approach to understanding the behavior of various fuel cycles and their impact on the associated policy choices



Nuclear Fuel Cycle Options Study

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- The Options Study is being conducted to assess the impact of alternative fuel cycles on issues ascribed to use of nuclear energy.
- Issues were collected from various surveys, public opinion polls, and policy statements.
 - Nuclear waste management
 - Proliferation risk
 - Safety and Security
 - Economics and affordability
 - Sustainability
- Relative importance has varied with time, events, and polling groups.
 - Qualitative and quantitative measures to identify impact of options
- Identify where a “significant” difference can be made
 - Assumed to be an order of magnitude or more
 - Evaluations of alternate fuel cycles with respect to an assumed reference of today’s once-through fuel cycle using LWRs





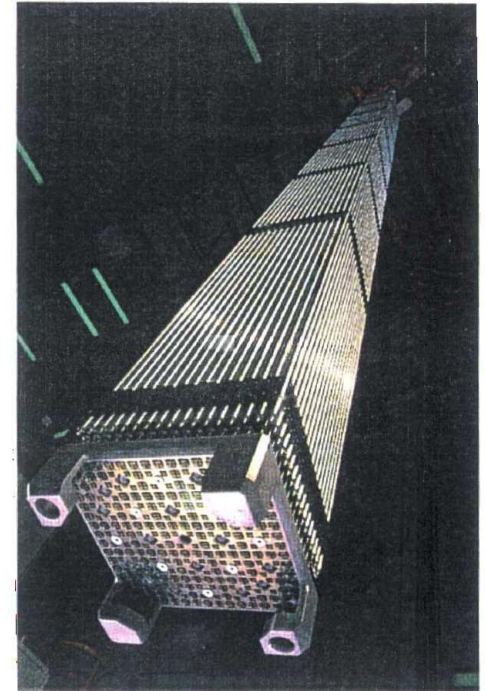
- **Once-Through Fuel Cycle – One pass through reactor, used fuel directly disposed in a geologic repository.**
- **Modified Open Cycle – No or limited separations and processing applied to used fuel to extract more energy.**
- **Full Recycle – All actinides important for waste management are recycled in thermal or fast spectrum systems to reduce radiotoxicity and more fully utilize uranium resources.**



Once Through Fuel Cycle

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- With once-through, used nuclear fuel is disposed in a repository.
- Uranium utilization is less than 1%.
- Fuel burnups have increased through the years.
- Higher burnups result in less spent fuel disposed but do not increase uranium utilization.
- Programs are pursuing advanced fuel designs that may double fuel burnups (100 GW/MTHM).
 - Fuels may required enrichments higher than 5%.
- Higher burnups results in less spent fuel disposed but similar amounts of actual waste (transuranics and fission products).





- With completely closed fuel cycles, high-level waste forms are disposed in a repository.
- Recycle of plutonium to LWRs as MOX increases uranium utilization, but it is still very low.
- Recycle all transuranics into fast reactors combined with breeding in depleted uranium can enable uranium utilization to approach 99%.
- Both aqueous and dry technologies are being considered for fuel processing.
- Both metal and oxide fuels are being considered for fast reactors.
- As part of FCRD new technologies are also being assessed.
 - Alkaline dissolution and separation, ionic liquid extraction and electrochemical separation, super critical fluid extraction, uranium crystallization, volatility approaches (airox, deox, fluoride volatility, etc), and zone refining



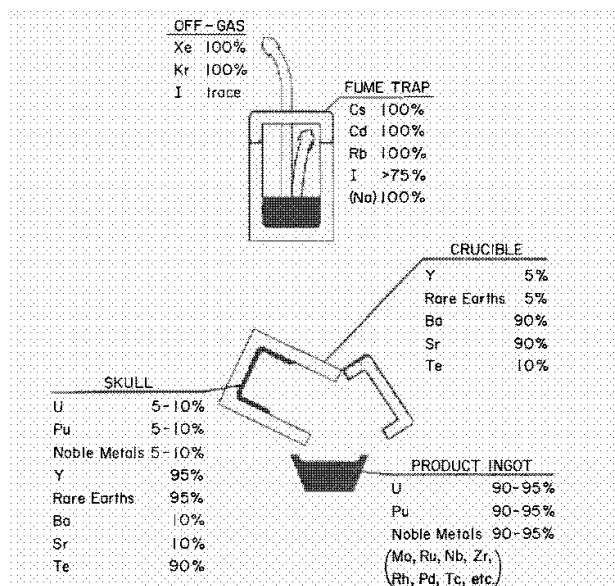


Modified Open Cycle

- Modified open cycles can provide benefits of both Open and Full Recycle fuel cycles.
- Modified open cycles involve reuse of fuel which may require some form of treatment.
- Treatment means modification of the used fuel.
- This could be as simple as heat treating the used fuel cladding or as complex as chemical processing and recladding the fuel.
- Some separations processes employed for full recycle may be used for the modified open cycle.



Oxide fuel after Voloxidation

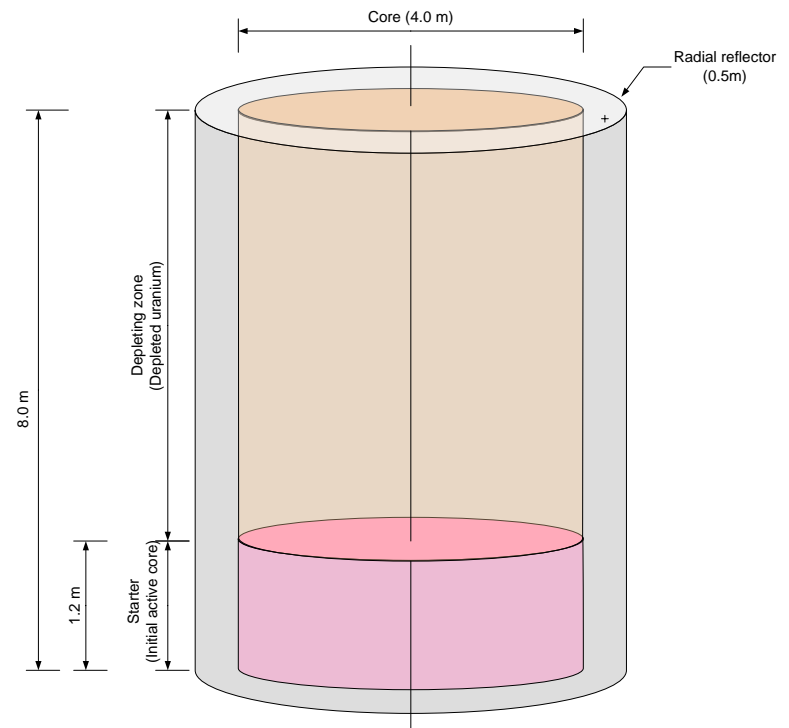


Melt Refining



Modified Open Cycle Examples

- Breed and burn concepts (including the traveling waves designs) both with and without fuel conditioning
- Deep burn of transuranics in high-temperature gas reactors (requires fuel processing)
- Deep burn of transuranics in inert matrix fuels
- DUPIC process for recycle of LWR fuel into CANDU reactors with thermal treatment of fuel
- Fission-fusion systems
- Accelerator driven systems



Reactor Core Design with Axial Propagation



Collaborating with Other DOE Offices

- **RW – Used and spent nuclear fuel disposition**
- **EM – Proposed research initiative on waste management technology development (e.g., salt disposal); waste forms**
- **NNSA – Domestic safeguards technology research and development; proliferation risk assessment tool development; international collaborations**
- **SC – Modeling and simulation, materials, nuclear physics, separations**



Focuses on development of technologies vital to the success of both tank waste treatment and closing the nuclear fuel cycle in the U.S.

- **Waste form development**
- **Waste form behavior in disposal environments**
- **Waste processing**
- **General waste chemistry**
- **Waste disposition options (e.g., salt)**
- **Public perception**



- **DOE's Fuel Cycle Research and Development Program is an integrated, goal-oriented, science-based program to provide fuel cycle and used fuel management options to future decision makers.**
- **Program is focused on development and assessment of technical options.**
- **Research is focused on improvements to direct disposal, modified open cycle, and full recycle.**
- **Talks that follow will address three key technical areas of the program.**
 - Separations
 - Fuels
 - Transmutation